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A MODEL OF THE INTERACTION BETWEEN THE SOLAR WIND AND AN INTERSTELLAR MEDIUM

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A MODEL OF THE INTERACTION BETWEEN THE SOLAR WIND AND AN INTERSTELLAR MEDIUM[1]

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ABSTRACT. A model of the interaction between the solar wind and an interstellar medium, based on the assumption that Coulomb collisions predominate in interstellar gas, is designed and described. Hydrodynamic equations are used to describe the flow.

Experimental investigations of interplanetary plasma by space vehicles have /41* established the fact of the existence of a supersonic flow of plasma from the sun. The results of these investigations do not contradict the existing theory concerning the solar wind (see [1, 2], for example). According to today's accepted solar wind theory, the plasma from the solar corona has already reached supersonic speed at a short distance from the sun (of the order of a few solar radii), the result of thermal expansion, after which the speed rapidly approaches the asymtote. This speed can be taken as constant for a distance equal to one astronomical unit (AU), approximately, so in the case of a spherically symmetrical flow there is a reduction in density as $1/r^2$ (r is the distance from the sun). According to Parker [1], the magnetic pressure of the total magnetic field of the sun at great heliocentric distances too drops as $1/r^2$, so that, because of its smallness as compared with the dynamic pressure of the solar wind, the latter cannot slow down the sun's magnetic field.

The reduction in the mass density ρ has the result of making the solar wind pressure insufficient for the solar wind to push itself into the interstellar medium at certain distances from the sun.

According to today's hypotheses, deceleration of the solar wind is the result of its interaction with the interstellar magnetic field, with interstellar gas, or with cosmic rays. From the assessments made in surveys [3, 4], as well as in reference [5], it follows that the domain of strong deceleration of the solar wind

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1. Presented by Academician G. I. Petrov, 20 February 1970.

* Numbers in the margin indicate pagination in the original text.

begins at the heliocentric distance; $r \sim 10 - 100$ AU, depending on the nature of the hypothesis advanced. And the nature of the interaction depends heavily on the degree of ionization of the interstellar medium.

Today, the degree to which the interstellar gas in the vicinity of the solar system is ionized is virtually unknown. However, assessments based on the scattering of solar L_α-radiation in galactic hydrogen [6], as well as the theoretical computation made for the HII zone for the sun [7], using rocket measurements of the far solar ultraviolet spectrum, have it that the zone of almost total ionization of the hydrogen extends for a distance of at least 10^3 AU. Moreover, the interstellar gas in the vicinity of the solar system can be ionized by radiation from the closest hot stars (such as γVel and ξPup, for example).

The model, which is suggested and designed in what follows, is based on the assumption that Coulomb collisions predominate in interstellar gas.

We shall take it that the solar wind is spherically symmetrical in the vicinity of the sun, and we shall consider its interaction with the interstellar gas moving relative to the sun. The problem then will have cylindrical symmetry.

We shall assume that the flow can be described by hydrodynamic equations. This assumption stems from the fact that solar wind ions, considered as probe ions moving in the field of charged particles of the interstellar medium, lose their directional momentum almost completely and transfer it to the electrons [8] of the interstellar plasma at distances $L \lesssim 1$ AU (the computation assumes the density and the temperature of the interstellar medium equal to $\rho_1 = 10^{-24}$ g/cm^3, $T_1 = 5 \cdot 10^3$ °K, and the velocity of the solar wind to be $v_2 = 3 \cdot 10^7$ cm/s). The electrons, in turn, decelerate the ions of the interstellar medium. Moreover, when two plasma flows merge, beam instability can result, and this too can determine scattering of charged particles. These processes can be considered to be effective collision mechanisms, precluding the possibility of the existence of multispeed streams of ionized gas, and the possibility of the mutual penetration of flows with the same speed. At the same time, as will be shown in what follows, the characteristic scale of the phenomenon has an order of magnitude of ten astronomical units. /4

The solar wind and the stream of interstellar gas move at supersonic speeds.

The Mach number $M_2 = \infty$ is a good approximation for the solar wind, so if we take the temperature of the interstellar gas as $T_1 \lesssim 5 \cdot 10^3$ °K, and its velocity as $v_1 \sim 20$ km/s, we obtain $M_1 \gtrsim 2$ for that gas. Figure 1 is the qualitative expression of the flow resulting from the interaction of supersonic flows. Two shock waves are formed, with the interstellar gas passing through one, and the solar wind through the other.

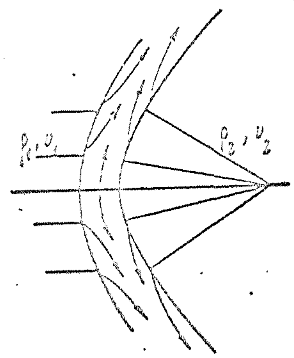

Figure 1

The gas is compressed in the layer between the shock waves, and its density is significantly greater than that of the surrounding medium. Busemann's method [9] can be used to arrive at a rough approximation of the shape of this compressed layer. Taking the layer of gas between the shock waves as thin (a surface) and assuming that the gas velocity across the layer does not change, we can write the law for the conservation of momentum in the gas layer in the projections on the normal and tangent to the layer in a heliocentric system of coordinates as

$$\rho_1 v_{1n}^2 = \rho_2 v_{2n}^2 + \frac{m v_l}{2\pi r \sin\varphi R};$$
$$\frac{d}{dl}(m v_l) = 2\pi r \sin\varphi\,(\rho_1 v_{1n} v_{1\tau} + \rho_2 v_{2n} v_{2\tau}). \qquad (1)$$

Here ρ_1 and v_1 are the density and the velocity of the interstellar gas; ρ_2 and v_2 are the same magnitudes for the solar wind; m is the mass of gas entering the layer in unit time from the solar wind and from the interstellar medium; R is the radius of curvature of this surface (the second term on the right-hand side of the first equation is the centrifugal force acting on the gas inside the domain of interaction); v_l is the mean velocity of the gas along the surface of discontinuity; the indexes n and τ refer to the projections of the corresponding velocities on the normal and the tangent, respectively; r and φ are the polar coordinates of the surface replacing the layer of gas between the shock waves /43 (Figure 2). The magnitudes m and R are found through the formulas (the primes signify differentiation with respect to φ)

$$m = \pi r^2 \rho_1 v_1 \sin^2\varphi + 2\pi r^2 \rho_2 v_2 (1 - \cos\varphi);$$
$$R = \frac{(r^2 + r'^2)^{3/2}}{(r^2 + 2r'^2 - r r'')}; \quad r = r(\varphi). \qquad (2)$$

Introducing angle x between the direction of velocity v_1 and the tangent to the surface, as well as angle y between the direction of the normal to the surface and the direction of the radius vector (Figure 2), and dropping v_1, m and R from Eqs. (1) and (2), we obtain the equation

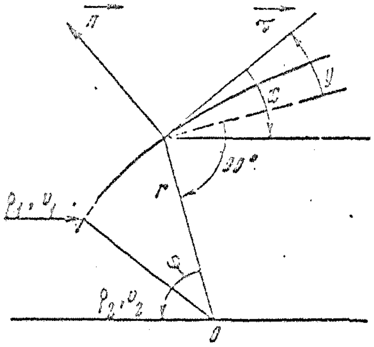

Figure 2

$$2\pi r^2 \sin\varphi\,(\rho_1 v_1^2 \sin x \cos x + \rho_2 v_2^2 \sin y \cos y) = \\ = \frac{1}{(r^2 + r'^2)^{1/2}} \left[\frac{2\pi r \sin\varphi\,(r^2 + r'^2)^{3/2}}{(r^2 + 2r'^2 - rr'')} \times \right. \\ \left. \times (\rho_1 v_1^2 \sin^2 x - \rho_2 v_2^2 \cos^2 y) \right]', \tag{3}$$

which, after computation of the relationships

$$\begin{gathered} \operatorname{tg} x = \operatorname{tg}[\pi/2 - \varphi + \operatorname{arc\,tg}(r'/r)]; \\ \operatorname{tg} y = r'/r; \\ v_{1n} = v_1 \sin x; \quad v_{1\tau} = v_1 \cos x; \quad v_{2n} = v_2 \cos y; \\ v_{2\tau} = v_2 \sin y, \end{gathered} \tag{4}$$

can be reduced to a complex, nonlinear, differential equation of third order relative to the function $r = r(\varphi)$, establishing the shape of the interface between the two plasma flows. This equation, in dimensionless form is (because of the cumbersome form of the equation obtained it will be written in general form only)

$$\xi''' = \psi_1(\varphi, \xi, \xi', \xi'') / \psi_2(\varphi, \xi, \xi', \xi'') \quad (r = r_0 \xi). \tag{5}$$

Here ψ_1, ψ_2 are known functions of their arguments; r_0 is the heliocentric distance to the surface of discontinuity when $\varphi = 0$; the magnitude r_0 can be determined from the relationship $\rho_1 v_1^2 = \rho_2 v_2^2$ (which follows from the first of the equations at (1) when $\varphi = 0$) when the equation of continuity for a spherically symmetrical solar wind $\rho v r^2$ = constant (v = constant) is used.

Eq. (5) is solved numerically for the boundary conditions

$$\xi = 1, \ \xi' = 0, \ \xi'' = 2/3 \quad \text{when} \quad \varphi = 0 \quad (\xi = r/r_0). \tag{6}$$

The second condition of Eq. (6) is the condition of symmetry for the problem, and the third condition makes it possible to move away from the singular point $\varphi = 0$, $r = r_0$ (when $\varphi \to 0$, the ratio ψ_1/ψ_2 is an indeterminancy of the form 0/0) along the integral curve passing through this point, and to numerically integrate Eq. (5). It should be pointed out that the right-hand side of Eq. (5), obtained through Eqs. (3) and (4), contains no dimensionless parameters, and that all

$r = r_0 \xi(\varphi)$ curves, defined by the solution for Eq. (5) for the boundary conditions of Eq. (6), are similar to each other (r_0 will depend on the relationship $\rho_1 v_1^2$ and $\rho_2 v_2^2$).

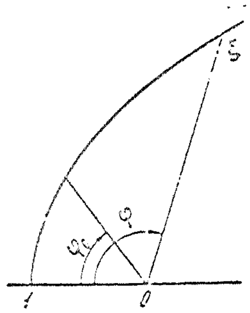

Figure 3

Figure 3 shows the results of the numerical computation for the function $\xi = \xi(\varphi)$. The angle between the plant of the ecliptic and the direction of movement of the sun relative to the interstellar medium is designated φ_0 in this figure. The distance to the surface of discontinuity along the beam $\varphi = \varphi_0$ is the distance to the surface of discontinuity in the plane of the ecliptic.

The measurements show that $\varphi \approx 53°$. What follows from the computations, therefore, is that $\xi(\varphi_0)/\xi(0) = r(\varphi_0)/r_0 \approx 1.2$.

Figure 4 shows the results of the computation for r_0 in terms of solar wind velocity, v_2, for various particle concentrations, n_2, in the earth's orbit, and when $\rho_1 \sim 10^{-24}$ g/cm^3, $v_1 \sim 20$ km/s.

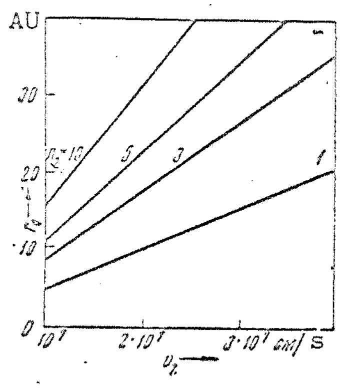

Figure 4

Specifically, when $v_2 \sim 3 \cdot 10^7$ cm/s, and $\rho_2 \sim 5 \cdot 10^{-24}$ g/cm^3 ($n_2 \sim 5$ cm^{-3}); we have $r_0 \sim 35$ AU. The distance to the surface of discontinuity in the plane of the ecliptic in this case is $r \sim 35 \cdot 1.2 = 42$ AU, that is, the surface of discontinuity is somewhere in the vicinity of the orbit of Pluto. This distance will decrease at lesser velocities, or at lesser densities, of the solar wind, naturally. /44

It should be pointed out that the assumption with respect to the layer between the shock waves being narrow will be upset, obviously, for large angles φ. The outer shock wave passes to infinity and degenerates into a characteristic, while the inner closes.

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